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Turbulent Heat Flux Measurements in a Transitional Boundary Layer

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addressing the effect of freestream turbulence on the transition of a zero pressure gradient boundary layer over a flat plate (Suder, O'Brien, and Reshotko 1988; Sohn, O'Brien, and Reshotko 1989; Sohn, Reshotko, and Zaman 1991).

One of the objectives in the experimental program was to measure the turbulent Prandtl number in the transitional boundary layers. A data base for this quantity was highly desirable in order to empirically model the heat transfer from turbine blades. The turbulent Prandtl number has been measured by several previous researchers in fully turbulent boundary layers (Chen and Blackwelder 1978; Senda, Suzuki, and Sato 1980; Blair and Bennett 1987). But such data for a transitional boundary layer have been lacking (Kim, Simon, and Kestoras 1989). However, such a measurement is difficult because a boundary layer in a highly disturbed environment undergoes bypass transition close to the leading edge resulting in a thin boundary layer, making probe resolution a serious problem. Thus, a miniature three-wire probe was designed for the present investigation, and custom fabricated, in order to measure the transitional boundary layer characteristics with reasonable spatial resolution.

The three-wire probe was used to make extensive measurements in transitional boundary layers under varying levels of freestream turbulence. The data of mean and rms velocities and the temperature, their correlations, spectra, and conditionally sampled velocity profiles have been reported in the paper by Sohn and Reshotko (1991). Most of these data compare well with previous measurements cited above, as well as with the recent numerical simulation of Rai and Moin (1991). However, the turbulent heat flux $\overline{(v't')}$ was repeatedly measured to be negative, in the near-wall region for transitional flows. The result was peculiar as it implied a counter-gradient heat transfer by the turbulent fluctuations. The wall was heated and the mean temperature profile in the boundary layer was as expected. But the turbulent heat flux was unexpectedly measured to be directed towards the wall.

As stated earlier, one original goal of the experimental program was to measure the turbulent Prandtl number for the transitional boundary layer. Thus, in view of the anomalous result for $\overline{v't'}$, which combined with the Reynolds shear stress provides the turbulent Prandtl number, it was necessary to undertake an extensive effort to identify and understand the source leading to the observed result. The present paper summarizes this effort.

EXPERIMENTAL FACILITY

The experiments were performed in a closed-loop, low-speed wind tunnel at NASA Lewis. A schematic of the tunnel is shown in figure 1. At the entrance to the test section, a double boundary layer bleed scoop is positioned. The large scoop is intended to remove the corner vortices and the boundary layer developed over the contraction nozzle wall. The small scoop, smoothly attached to the test surface, serves as the leading edge of the test plate. To increase the level of freestream turbulence in the test section, different types of grids were positioned in the flow conditioning chamber (see fig. 1). The test surface was uniformly heated (to maintain constant heat flux) using a 0.025 mm thick inconel foil heater. At each operating condition, zero pressure gradient was ensured in the test section by adjusting the inclination of the test section ceiling. Unless otherwise stated, the freestream velocity (U_e) was 30.5 m/s, and the heating was 350 W/m^2. For further description of the experimental facility and instrumentation, refer to Sohn and Reshotko (1991).

A miniature three-wire probe (fabricated by DANTEC Corp.) was used to simultaneously measure the instantaneous streamwise and normal components of velocity and the temperature. A schematic of the probe is shown in figure 2(a). The three-wire probe was designed on the requirement of having good spatial resolution and the ability to make measurements as close to the wall as possible. The X-shaped velocity sensors are 2.5 μm gold plated tungsten wires with sensing lengths of 0.5 mm. The temperature sensor is an unplated 1 μm

platinum wire with a length of 0.35 mm. It is located on one side of the X-element and is oriented normal to the streamwise direction. The separation distance between adjacent sensors is 0.35 mm (see fig. 2(a)). A photograph of the probe tip is shown in figure 2(b).

RESULTS

Earlier measurements with a single-wire probe had revealed that with grid 1 (freestream turbulence level of about 1 percent) the flow in the measurement domain (streamwise distance, X = 12.7 to 50.8 cm) nearly spanned the entire transitional regime from laminar to fully turbulent states. Thus, the grid 1 case was chosen for most of the three-wire measurements presented in this paper.

Figure 3(a) shows mean and rms profiles of the temperature and the streamwise and normal velocities obtained at X = 27.9 cm. The nominal intermittency at this location was about 0.55. Mean velocity (U) and temperature (T) profiles measured with the three-wire probe show smooth variation from near-wall to the edge of the boundary layer and are in good agreement with corresponding data obtained with a single-wire probe (the normal mean velocity V is discussed later). The rms velocity profiles of u' and v' show that a large degree of anisotropy exists in the transitional boundary layer especially near the wall, which diminishes farther away from the wall. The magnitudes and trend of the profiles of u' and t' are quite similar to each other and are also in agreement with previous data (Kim et al. 1989).

The correlation coefficient profiles of $-\overline{u'v'}$, $-\overline{u't'}$ and $\overline{v't'}$ are shown in figure 3(b), for the same flow condition as in figure 3(a). The $-\overline{u'v'}$ (Reynolds shear stress) profile shows nearly constant plateau value of 0.3 in the middle of boundary layer. The general trend and magnitudes are similar to the data obtained by others for transitional boundary layer with comparable intermittency (Kuan and Wang 1990). Note that the amplitudes of $-\overline{u'v'}$ are positive throughout the boundary layer. Essentially a similar comment can be made for the $-\overline{u't'}$ profile. Thus, the mean, rms and the correlation profiles discussed so far are all "well behaved." Furthermore, the energy balance was checked by comparing the enthalpy thickness obtained from the wall measurements and the profile measurements (see fig. 45 of Sohn and Reshotko 1991). The streamwise variations of the enthalpy thickness measured by the two methods, for the flow conditions considered herein, were essentially identical. However, as shown in figure 3(b), the turbulent heat flux $\overline{(v't')}$ is measured to be negative throughout the boundary layer. Such negative value of $\overline{v't'}$ is unexpected because it represents a counter-gradient heat transfer by the turbulent fluctuations, and is the focus of this paper.

The $\overline{v't'}$ profiles measured at several streamwise stations between X = 22.9 and 50.8 cm are shown in figure 4. Also included in this figure are the profiles for fully turbulent boundary layer obtained with grid 3 (nominal freestream turbulence level of 5 percent) for farther downstream locations. The nominal intermittency for the grid 1 case ranged from 0.34 at X = 22.9 to 0.99 at X = 50.8 cm. These profiles indicate that there is a clear trend of increasing $\overline{v't'}$ with increasing intermittency or Reynolds number and the negative values of $\overline{v't'}$ occur especially in the near-wall region for transitional flows. As the fully turbulent condition is approached, the measured profiles approach the shape observed by previous researchers for turbulent boundary layers (Chen and Blackwelder 1978; Senda et al. 1980; Blair and Bennett 1987). However, even for the case at X = 114.3 cm with grid 3 ($Re_\theta \approx 3200$), the peak values are somewhat lower than the peak values measured by other researchers (typically 0.5). The present turbulent boundary layer profile shows a constant plateau value of about 0.4 in the region of $0.4 < y/\delta_{0.995} < 0.8$. Furthermore, negative values are observed in a small region very close to the wall. These measurements were repeated and reproduced several times.

As a double check on the sign of $\overline{v't'}$, the cross-correlation between the temperature signal and the unlinearized normal velocity signal was measured with an analog correlator (Nicolet 660B). The measurements were performed for grid 3 case at X = 50.8 cm for two y locations between which the sign of $\overline{v't'}$ clearly changed. These two y locations are indicated in the corresponding profile in figure 4 by the two solid data

negative closer to the wall, commensurate with the data of figure 4. These data establish that the negative $\overline{v't'}$ was not due to any obvious error linked to the instrumentation or the digital postprocessing.

Possible peculiarity in the flow facility and instrumentation was considered. It was suggested that there might be cold spots on the heated wall where the heat flux would be directed towards the wall. However, such a possibility could be refuted from the mean temperature profiles. Such a cold spot would be expected to distort the mean temperature profiles which is not the case as shown in figure 3(a). Contribution from electronic noise in the measurement was also considered. Data obtained for the unheated boundary layer showed a nonzero value for t' due to the electronic noise (Sohn and Reshotko 1991). To check the effect of the noise on the correlation of v' and t', measurements were performed for both heated and unheated boundary layers at $X = 50.8$ cm for grid 3 and the results are shown in figure 6. Note that the temperature difference used in the normalization for the unheated boundary layer is the same as that for the heated case. It is clear that the residual measurement noise is minimal, and should not have any influence on the sign of the correlation between v' and t'.

Since the spanwise separation of the velocity and the temperature sensors in the three-wire probe was relatively large, it was thought that the measurements suffered from averaging over too large a spanwise domain. For a fully turbulent boundary layer at $X = 50.8$ cm for grid 3 ($U_e = 30.5$ m/s), the spanwise distance between the velocity and the temperature sensors in wall units, S^+, was about 46. Ligrani and Bradshaw (1987) suggested the criterion of S^+ less than 20 for resolving the fine scale near-wall turbulent fluctuations. With fixed probe geometry, one way to reduce S^+ was to lower the freestream speed. Measurements of $\overline{v't'}$ with $U_e = 13.7$ m/s ($S^+ = 22$) and $U_e = 7.6$ m/s ($S^+ = 13$) were performed and the profiles are shown in figure 7. While the boundary layer is fully turbulent ($U_e = 30.5$ and 13.7 m/s), noticeable increase in the amplitude of $\overline{v't'}$ is observed with decreasing S^+. Lowering the freestream velocity even more ($U_e = 7.6$ m/s) does not increase the amplitudes further; in fact, the peak amplitudes are observed to reduce. This is due to the fact that the boundary layer is not yet fully turbulent (still transitional) for the $S^+ = 13$ case at the measurement location. It is apparent that averaging due to large probe size reduces the amplitude over most of the boundary layer. However, note in figure 7 that for all S^+ there is a region near the wall where $\overline{v't'}$ is negative. This is more so for the transitional boundary layer case. It is, therefore, fair to say that the negative $\overline{v't'}$ is not due to probe averaging and appears to be characteristic of the transitional boundary layer.

A suggestion was made that the "streaky structure" in the boundary layer, together with the large probe size, could be responsible for the negative $\overline{v't'}$ amplitudes (J.M. Wallace, private communication). Turbulent boundary layers are known to be characterized by the streaky structure in the near wall region. These are presumably streamwise vortical structures with typical spanwise spacing of about 100 wall units. Thus, if a probe has its sensors spaced approximately half this distance, it is possible that one sensor would be in a downwash region while the other would be in an upwash region. Such a situation quite conceivably could result in a negative correlation. Note that in some cases of the present measurements the spanwise spacing of the velocity and temperature sensors (S^+) was indeed close to 50 wall units. Even though the present measurements were in the transitional region and the concept of "streaky structure" pertains to fully turbulent boundary layers, it was felt that further investigation of this possibility was called for. It was reasonable to expect that if indeed there existed a well defined streaky structure (or perhaps, a Görtler vortex like structure), the spanwise variation of a suitable correlation quantity should exhibit a commensurate waviness.

Correlation measurements were performed with varying separation of two different probes in the spanwise direction. A single-wire temperature probe was held fixed at mid-span, at $X = 22.9$ cm for grid 1 with $U_e = 30.5$ m/s. An X-wire probe, located at the same streamwise station, was traversed in the spanwise direction. When placed close to each other, the probe combination approximated the dimensions of the three-wire probe. From this position the X-wire probe was moved away in small increments while the data were recorded digitally. Figure 8(a) shows the spanwise variation of $\overline{v't'}$ acquired at a normal distance, $y^+ \approx 30$.

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$U_e = 30.5$ m/s. An X-wire probe, located at the same streamwise station, was traversed in the spanwise direction. When placed close to each other, the probe combination approximated the dimensions of the three-wire probe. From this position the X-wire probe was moved away in small increments while the data were recorded digitally. Figure 8(a) shows the spanwise variation of $\overline{v't'}$ acquired at a normal distance, $y^+ \approx 30$. When z^+ (spanwise distance in wall units) is small, simulating the configuration of the three-wire probe, $\overline{v't'}$ amplitude is clearly negative. *Since a set of different probes were used for these measurements, this is added confirmation that the negative values are not due to any peculiarity of the three-wire probe itself.* As z^+ is increased, $\overline{v't'}$ increases to zero and stays zero for larger values of z^+. The small undulations in this curve varied somewhat with varying measurement height y^+, but it is clear that any definitive spanwise structure is absent. The streamwise velocity fluctuation, u', corresponding to the data of figure 8(a) is shown in figure 8(b). Again, no clear spanwise variation is discernible. Thus, these data negate the presence of any strong spanwise organization such as would be expected from a "streaky structure" or Görtler type instability. Therefore, the assumption that the negative $\overline{v't'}$ correlation is due to such a structure, when measured with a probe of certain size, may not be correct.

An attempt was made to assess if other terms in the energy equation were contributing to the observed discrepancy. First, the profiles of the heat flux in the streamwise direction, $\overline{u't'}$, measured for the grid 1 case, are shown in figure 9. Even though the typical assumption that the streamwise variation of $\overline{u't'}$ is negligible may be correct in a fully turbulent boundary layer, it may not be so in the transitional boundary layer. For a given vertical distance, there is a substantial streamwise variation of $\overline{u't'}$, as is clear from figure 9. The sign of the streamwise gradient of $\overline{u't'}$ changes around $X = 33.0$ cm. Contribution of the streamwise variation of $\overline{u't'}$ to the energy balance over a control volume was considered. The general energy equation,

$$U\frac{\partial T}{\partial x} + V\frac{\partial T}{\partial y} = \frac{\partial}{\partial x}\left(\alpha\frac{\partial T}{\partial x} - \overline{u't'}\right) + \frac{\partial}{\partial y}\left(\alpha\frac{\partial T}{\partial y} - \overline{v't'}\right) \tag{1}$$

and the continuity equation,

$$(T - T_e)\left(\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y}\right) = 0 \tag{2}$$

were combined and integrated from $y = y_0$ to $y \to \infty$. The resulting equation is,

$$\frac{d}{dx}\int_{y_o}^{\infty}\left[U(T - T_e) - \alpha\frac{\partial T}{\partial x} + \overline{u't'}\right]dy = \left|V(T - T_e) - \alpha\frac{\partial T}{\partial y} + \overline{v't'}\right|_{y=y_o} \tag{3}$$

Note that the equation applies to a control volume extending over the streamwise distance dx, and over the normal distance from $y = y_0$ to the freestream.

From the experimental data, values of each of the six terms in equation (3) could be estimated. Table I shows these values calculated for an arbitrarily chosen $y_0 \approx 1.12$ mm. It is clear that the contribution of $\overline{u't'}$ is still an order of magnitude smaller than that of $\overline{v't'}$ in the energy balance. It is also obvious from a comparison of the sums that there is an imbalance in the measured quantities, especially in the upstream region.

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The first term on the left hand side of equation (3) (table I) can be seen to be large. The variation of the integrand, $U(T-T_e)$ is shown in figure 10. The area under these curves on the right hand side of the vertical line $(y = y_0)$ is consistently and monotonically increasing from $X = 22.9$ cm downstream. Scrutiny reveals that this term, dominating the summation of the terms on the left hand side of equation (3) (table I), is reasonably well behaved. This is demonstrated in figure 11. The sum of the integrals on the left hand side is plotted as a function of X and compared with the wall input. The gradient from the data points is expectedly larger than the gradient representing the wall input. Note that since the integration is done from $y = y_0$, the measured values for the sum is expected to be near zero up to the X-station where the thermal boundary layer just exceeds y_0. The separation of the measured curve and the curve obtained from the wall input is thus expected; the separation should depend on the value of y_0. The measured data points may be expected to asymptotically coincide with the curve obtained from the wall input at far downstream locations, where the boundary layer thickness is much larger than y_0. Thus, a higher slope from the measured data should also be expected. In summary, the first term in equation (3), dominating the left hand side, must have been measured with reasonable accuracy. This is in agreement with the good comparison of the enthalpy thicknesses obtained from the wall measurements and profile measurements, mentioned earlier.

The thermal boundary layer development in relation to the lower limit, $y = y_0$ in the integration, is shown at the top of figure 11. The curve for the $\delta_{.995}$ variation is based on data available for the transitional region (22.9 cm < X < 50.8 cm). For the upstream and downstream ends of the curve, a laminar and a fully turbulent correlations were used, respectively.

The second and third terms on the left hand side of equation (3) are measured to be small (table I) as expected. Thus, attention should be focused on the terms of the right hand side of equation (3) for the discrepancy in the energy balance. The magnitude of the first term on the right hand side of equation (3) can be seen to be large. The variation of the term $V(T-T_e)$ is shown in figure 12. Note that the values in table I are the ones at $y = y_0$ marked by the vertical line. It can be seen that the term at the three upstream locations is slightly negative but represent the magnitudes that dominate the right hand side. The value at the other three downstream locations is positive and relatively large. Since the value of $(T - T_e)$ remains relatively unchanged, the value of $V(T - T_e)$ is essentially dominated by the measured value of V.

The V profiles corresponding to the data of figures 10 and 12 are shown in figure 13(a). The same data are replotted in figure 13(b) as a function of nondimensional y, for direct comparison with figures 4 and 9. For the upstream locations, V is measured to be negative near the wall. Negative values for V in the transitional region are not unexpected, since the laminar mean velocity profile has to develop into the fuller turbulent velocity profile through the transition region. Thus, a negative mean V may be expected near the wall, especially if the transition is relatively abrupt. In fact, computational studies by S.T. Wu as well as by T.H. Shih and co-workers (private communications), do show negative values for V in the transitional region near the wall. However, the measured negative magnitudes (fig. 13) are about an order of magnitude larger than the values computed.

The magnitude of V near the edge of the boundary layer (V_e/U_e) is expected to be equal to the streamwise gradient of the displacement thickness, $d\delta^*/dx$. Note that the trend in V_e/U_e with increasing X (fig. 13) is as expected. It is largest in the transitional region because the increase of δ^* with X is the fastest in that region. However, the measured slopes, $d\delta^*/dx$ are found to be much smaller than the measured values of V_e/U_e. For example, the measured value of V_e/U_e is about 0.008 at $X = 50.8$ cm as shown in figure 13, while the value of $d\delta^*/dx$ is approximately 0.003 at the same streamwise location. Therefore, it appears likely that the imbalance in the energy equation is primarily due to inaccuracy in the measured V.

The calibration of the three-wire probe, and its accuracy for resolving small V, was checked by slanting the probe in a uniform stream and changing the angle of inclination in small increments. This yaw calibration

checked out to be fine. Thus, the anomaly between V_e/U_e and $d\delta^*/dx$ is surprising and unresolved. Furthermore, let us mention that even if the values of V computed by S.T. Wu were to be used to calculate the term $V(T - T_e)$ in table I, the energy would still remain unbalanced. The accuracy of the magnitude of V and its consequence on the energy balance in the transitional region should be deemed as inconclusive.

Let us emphasize that the V velocity, which is small and obtained by differencing two large voltages, is inherently more difficult to measure and prone to inaccuracies. Relatively, the fluctuating quantities are larger, and therefore, $\overline{v't'}$ should be more accurately measurable, just as v' or t' themselves are. Thus, the measured values of $\overline{v't'}$, even though they could not be checked by the energy balance, are thought to be relatively accurate. If there are inaccuracies, it is not clear at this time what the sources are.

Recently, Shome and Wang (1991), in an experiment over a heated flat plate, also encountered negative $\overline{v't'}$ amplitudes measured with a similar three-wire probe. The measurements were conducted for $U_e \approx 13$ m/s with freestream turbulence level of 0.9 percent. A set of their data for a transitional boundary layer ($Re_x = 8.82*10^5$), is shown in figure 14. Comparing with the present data, say, for the grid 1 case at $X = 50.8$ cm in figure 4 (note that y/δ range is about twice that in fig. 4), the similarity is unmistakable. The data show a small positive value around $y/\delta \approx 0.4$ but is clearly negative near the wall with a trend that is similar to the present data. The data of Shome and Wang (1991) seem to suffer from more scatter and it is not clear why the correlation becomes negative again in the freestream. The present data indicate a zero amplitude as the freestream is reached.

SUMMARY

While investigating the characteristics of a heated transitional boundary layer, the turbulent heat flux was unexpectedly measured to be negative in the near-wall region. Repeated measurements under varying conditions yielded this result in spite of the fact that many other quantities, viz., the mean U, T, and rms u', t' as well as Reynolds shear stress, were well behaved. Reducing the probe size in wall units (S^+) did not result in the positive $\overline{v't'}$. Measurements negated the possibility that the negative $\overline{v't'}$ resulted from organized spanwise structure in the boundary layer. A energy balance check clearly showed that the contribution from the $\overline{u't'}$ term was much smaller than that from $\overline{v't'}$. It also shows values of V (and possibly v') that were much larger than expected. Nevertheless, the negative $\overline{v't'}$ was confirmed by measurements with a different set of probes and was also reported recently by another researcher from experiments in another facility. The source of this anomalous result remains unclear.

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TABLE I.—ENERGY BALANCE

[Dimension: m/s °C.]

X [m]	$\dfrac{d}{dx}\int_{y_o}^{\infty} U(T-T_e)\,dy$	$\dfrac{d}{dx}\int_{y_o}^{\infty} -\alpha\dfrac{\partial T}{\partial x}\,dy$	$\dfrac{d}{dx}\int_{y_o}^{\infty}\overline{u't'}\,dy$	Sum	$V(T - T_e)\big|_{y_o}$	$-\alpha\dfrac{\partial T}{\partial y}\big|_{y_o}$	$\overline{v't'}\big|_{y_o}$	Sum
0.2286	0.426[a]	$0.336*10^{-3}$	-0.0113	0.415[a]	-0.19	0.065	-0.098	-0.223
0.2794	0.340	$0.136*10^{-3}$	-0.0161	0.324	-0.21	0.057	-0.142	-0.295
0.3302	0.347	$-0.249*10^{-4}$	-0.0126	0.334	-0.04	0.034	-0.127	-0.133
0.3810	0.320	$-0.441*10^{-4}$	-0.00175	0.318	0.58	0.021	-0.135	0.466
0.4445	0.337	$-0.395*10^{-5}$	0.00354	0.341	0.71	0.013	-0.083	0.640
0.5080	0.599[a]	$-0.751*10^{-5}$	0.00438	0.603[a]	0.67	0.012	-0.072	0.610

[a]These values are subject to large errors in numerical differentiation. See figure 11.
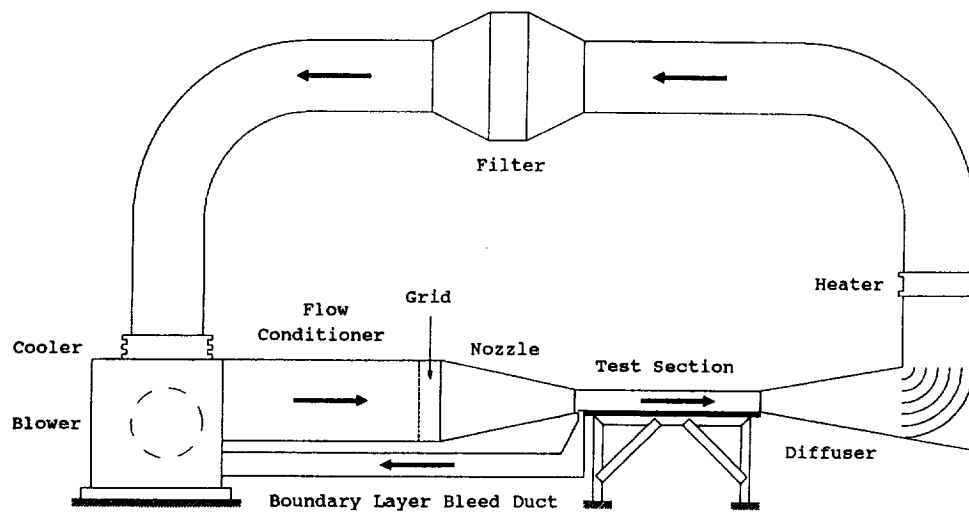
Fig. 1   Schematic diagram of the wind tunnel.
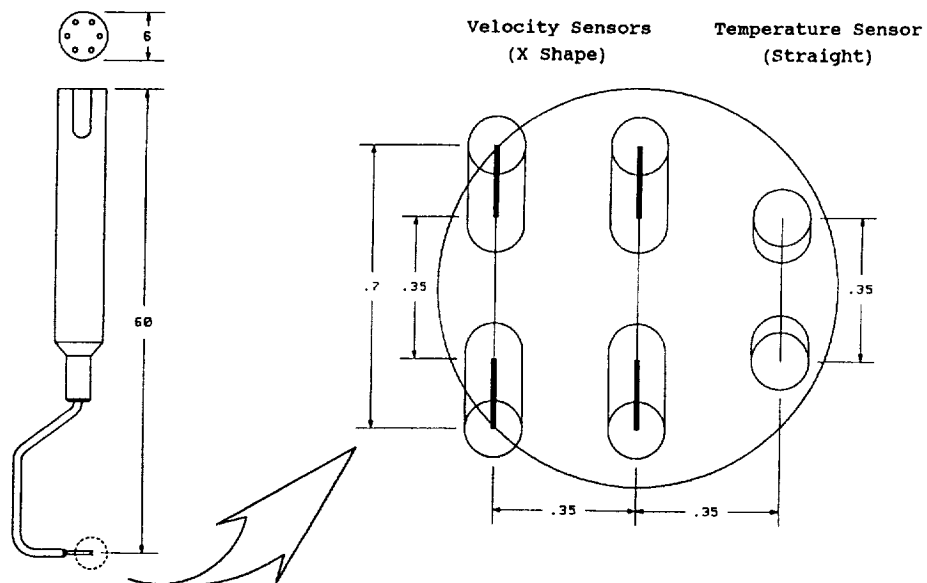
Fig. 2(a)   Schematic of the 3-wire probe. Dimensions are in mm.
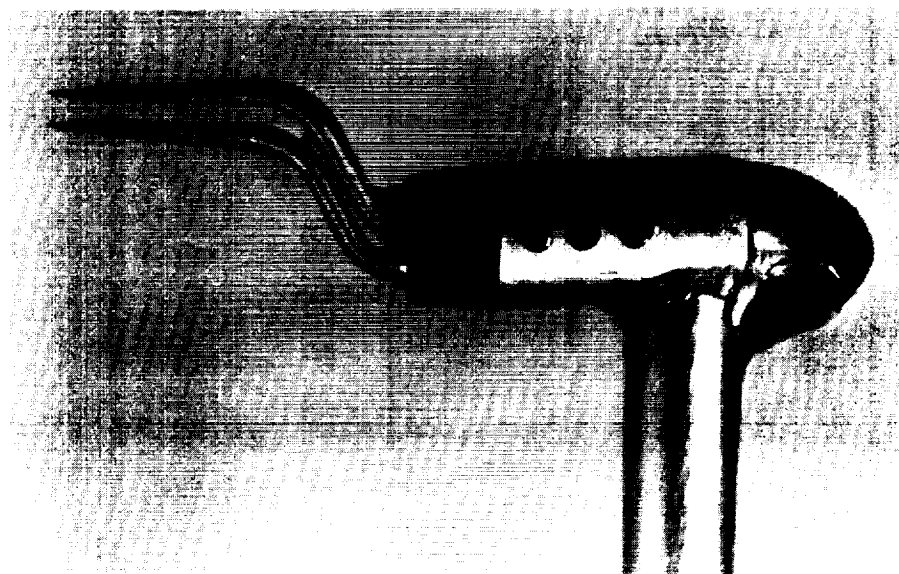
Fig. 2(b)   Photograph of the 3-wire probe tip.
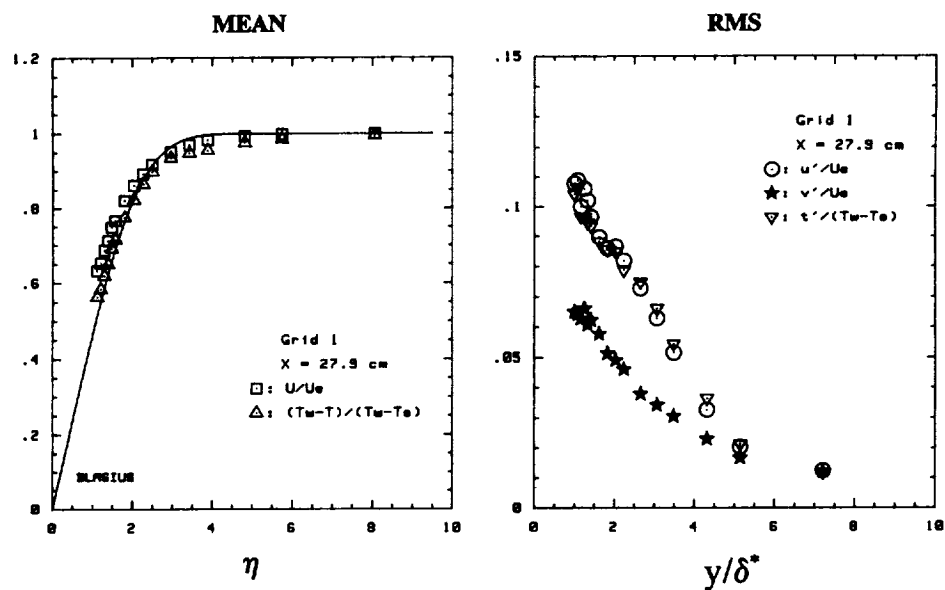
Fig. 3(a)   Mean and rms profiles of velocity and temperature measured
with the 3-wire probe.

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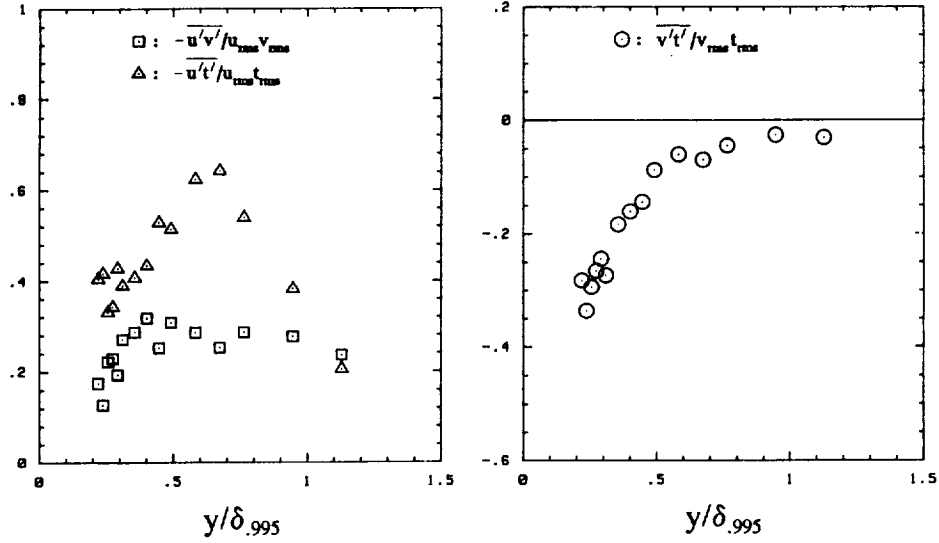
Fig. 3(b)   Correlation coefficient profiles measured with 3-wire probe for
grid 1 at X=27.9 cm.
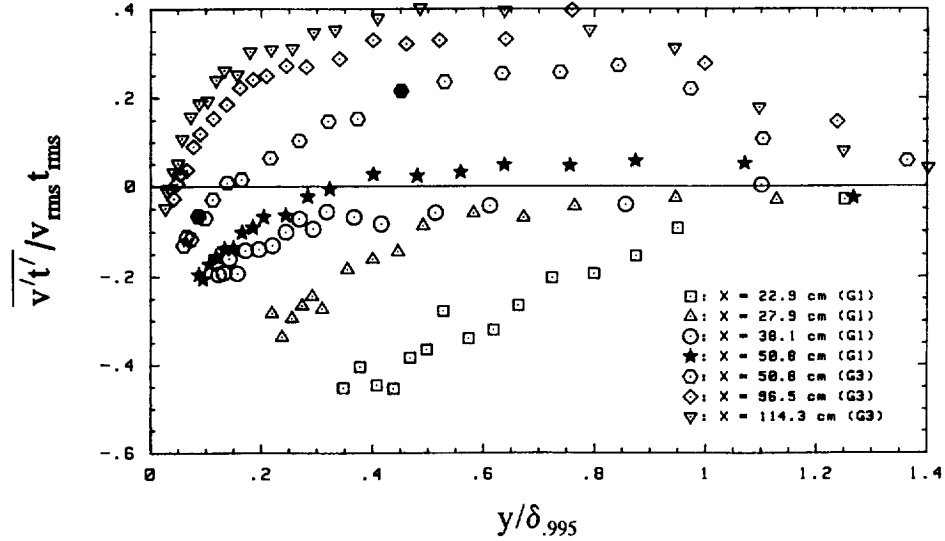
Fig. 4   Correlation coefficient profiles of v' and t' for indicated grid and
X locations. The nominal intermittency values are 0.34, 0.55,
0.93, 0.99 for grid 1 cases (G1) and are all 1.0 for grid 3 (G3).
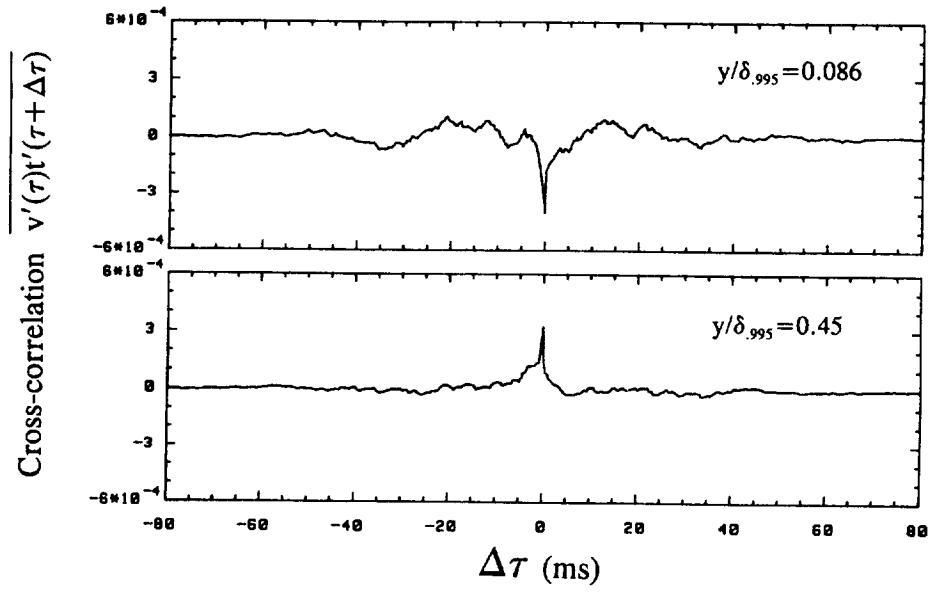
Fig. 5   Sign check of turbulent heat flux at X=50.8 cm for grid 3.
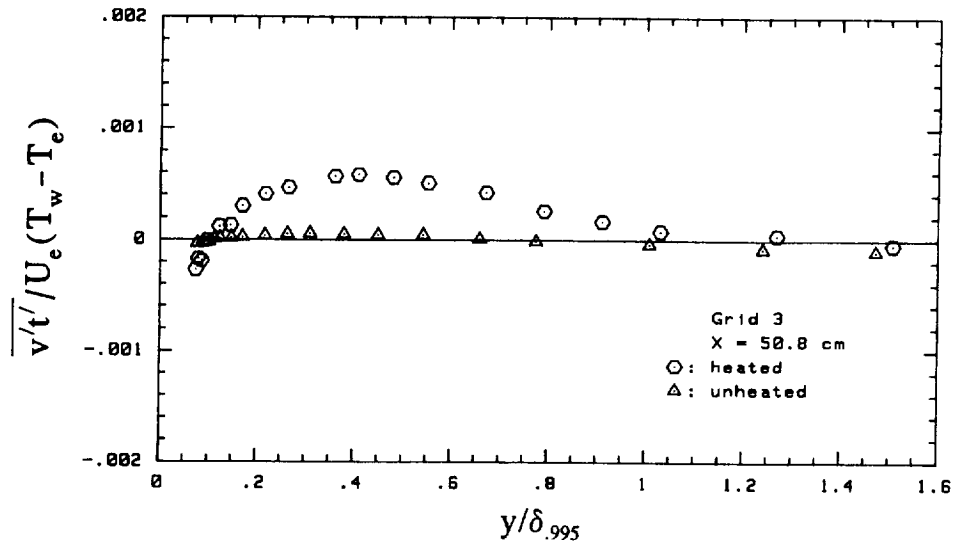
Fig. 6   Effect of electronic noise on the turbulent heat flux.

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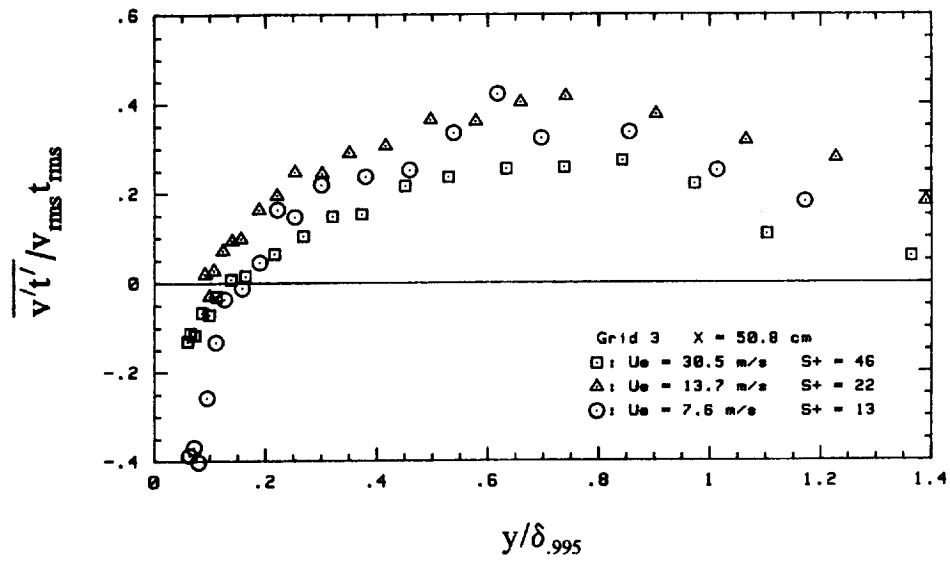
Fig. 7 $\overline{v't'}$ profiles measured with different spanwise separation of the velocity and temperature sensors (S^+).
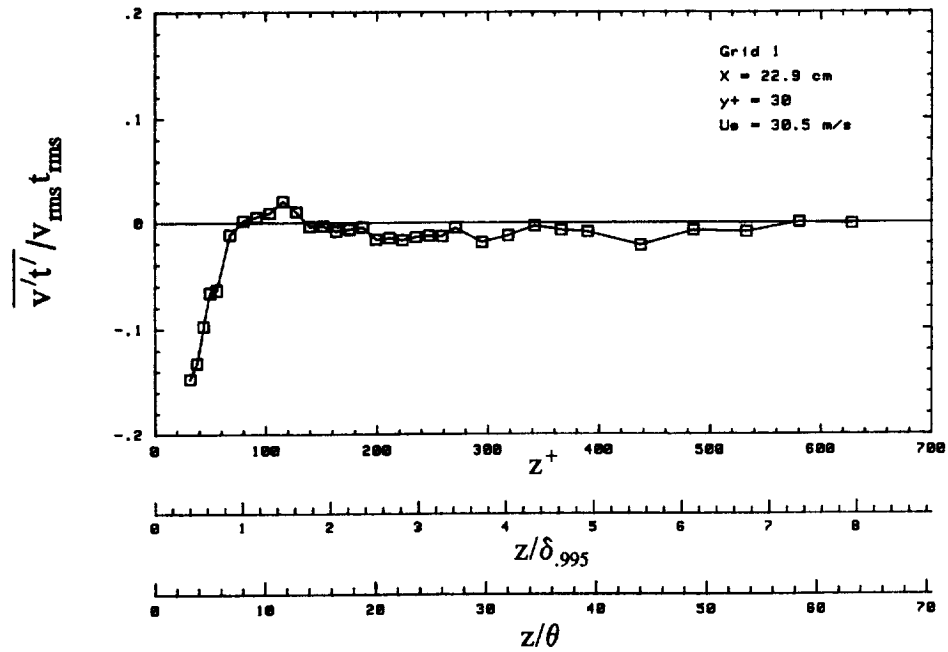
Fig. 8(a)   Spanwise variation of turbulent heat flux.

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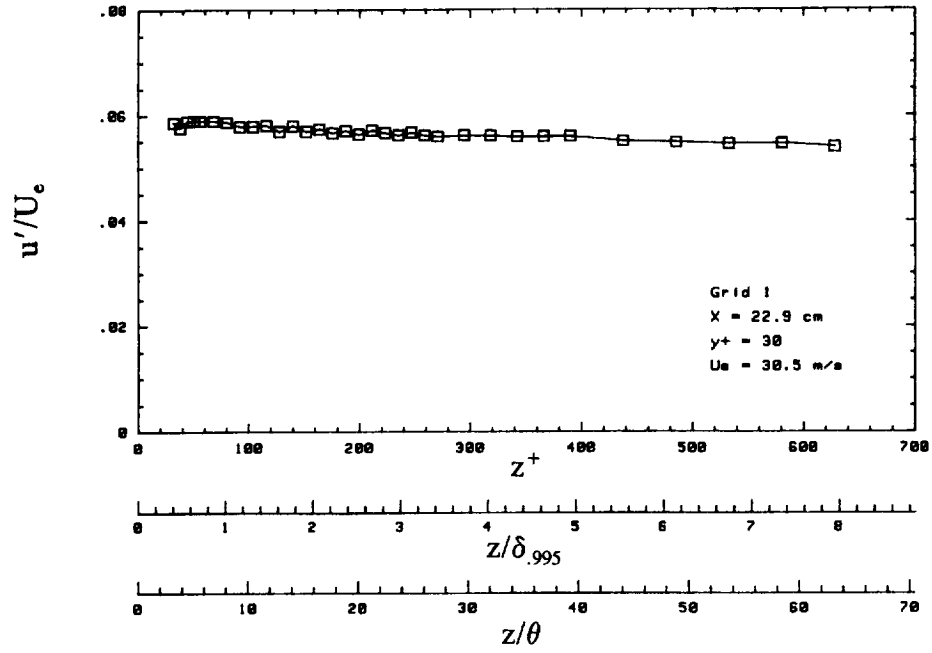
Fig. 8(b)   Spanwise variation of u'.
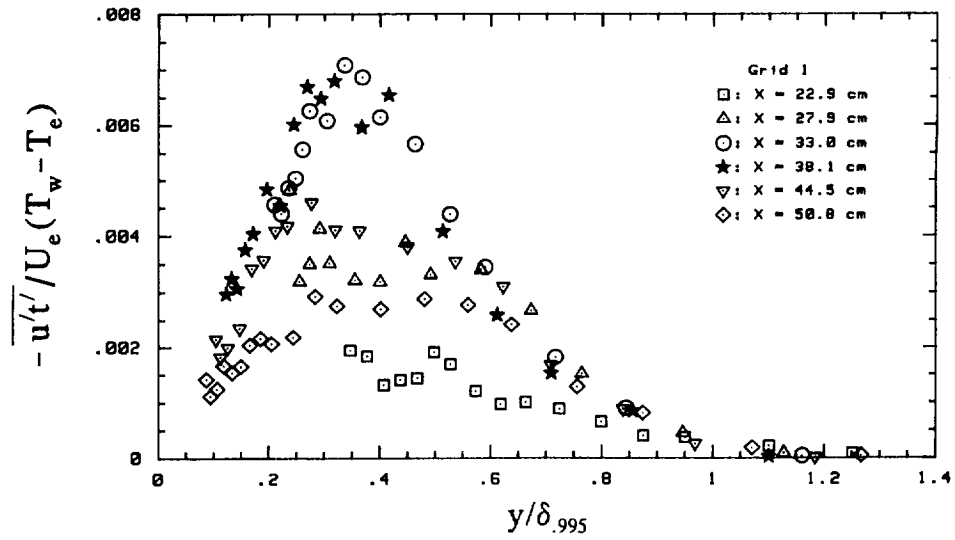
Fig. 9   Profiles of $\overline{u't'}$ at indicated X locations.

15
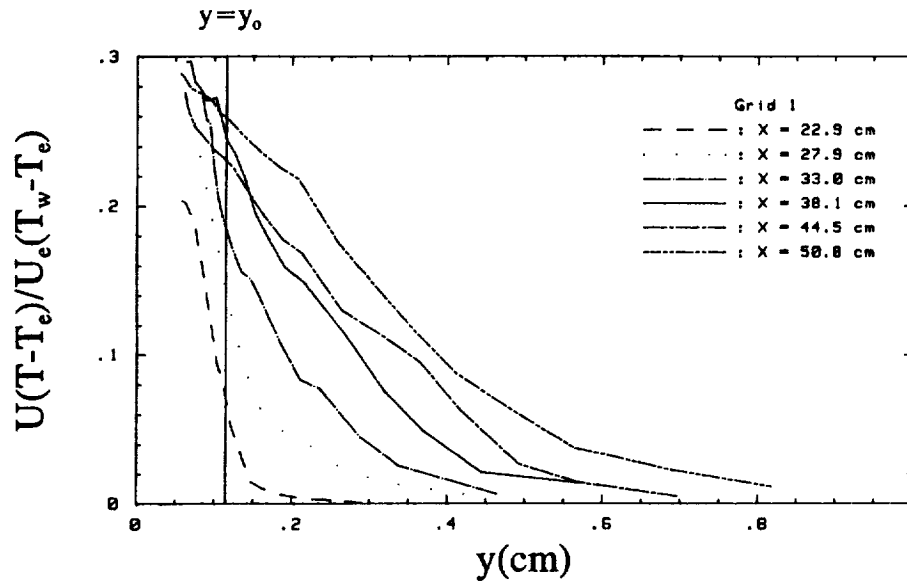
Fig. 10   Profiles of U(T-T$_e$).
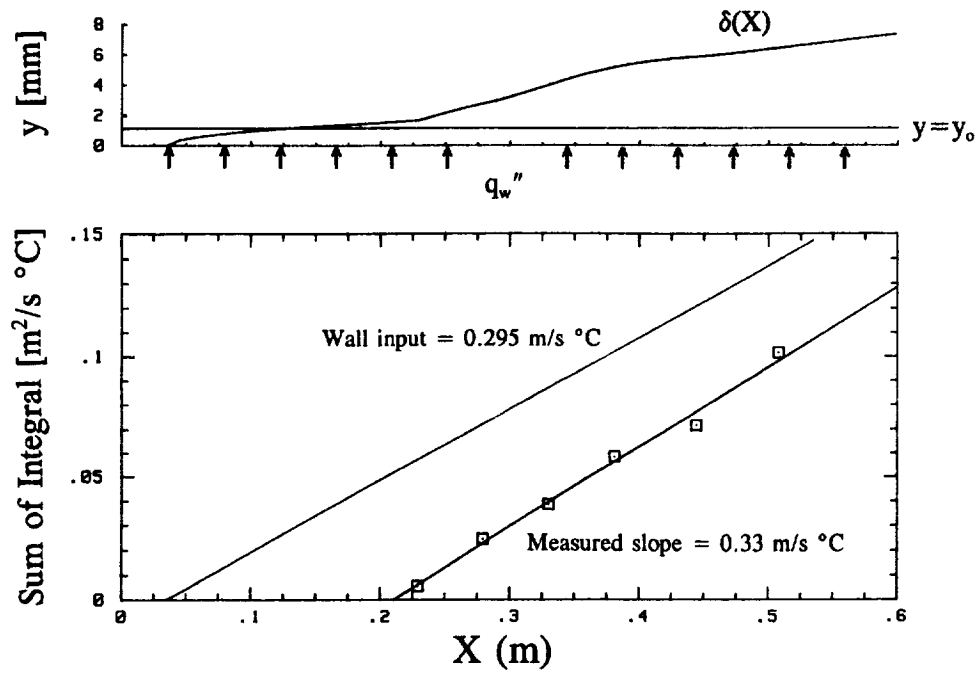
Fig. 11   Summation of integrals on the left hand side of eq.(3) compared to wall heat input.
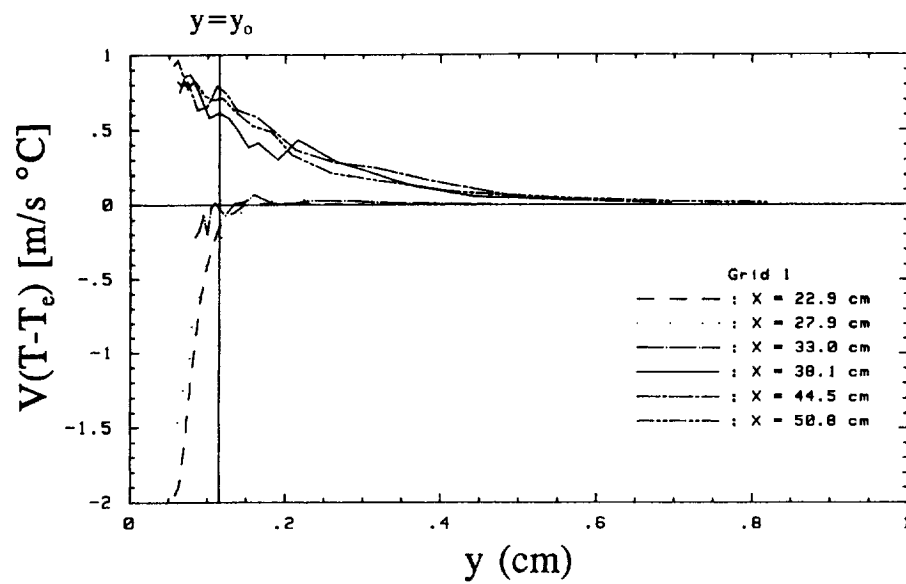
Fig. 12   Profiles of V(T-T$_e$).
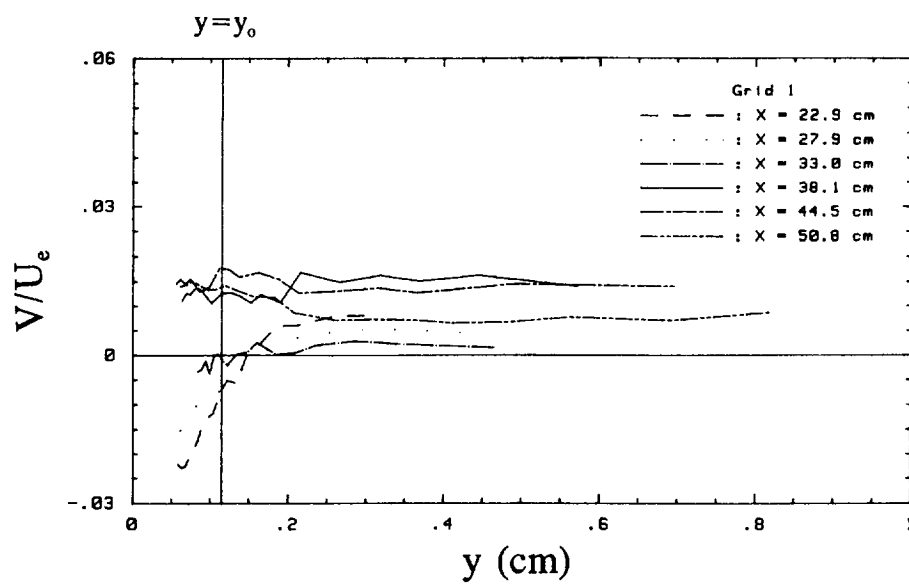
Fig. 13(a)   Profiles of mean normal velocity V as a function of
dimensional distance y.
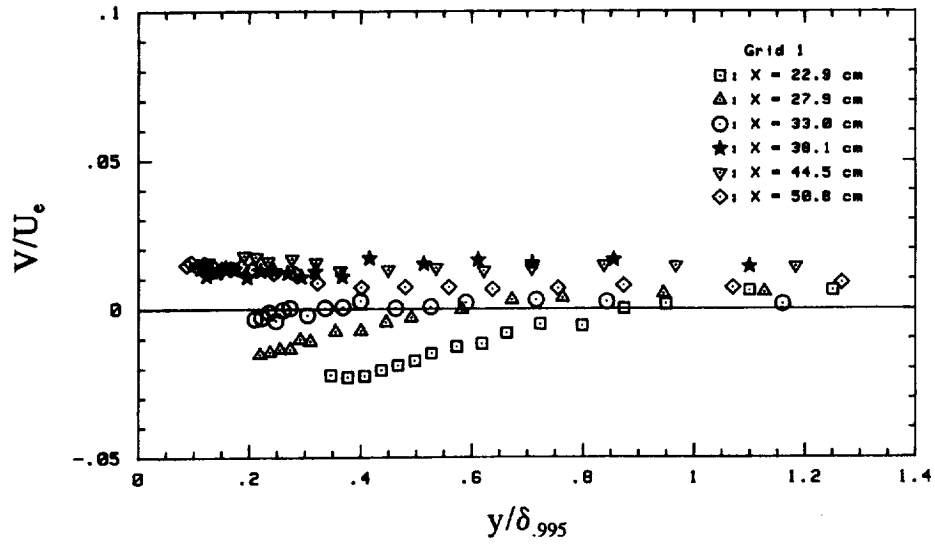
Fig. 13(b)   Profiles of mean normal velocity V.
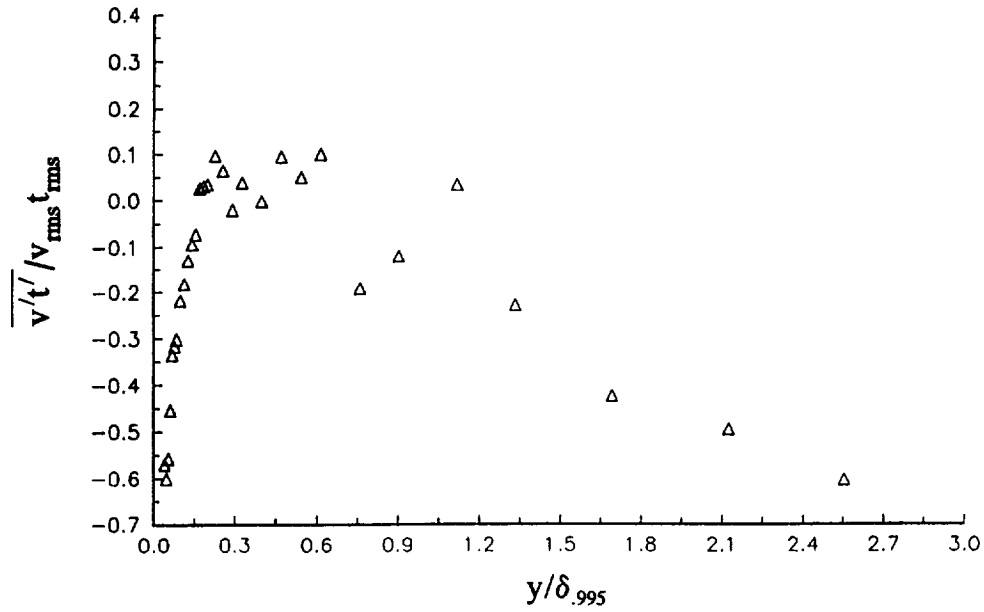
Fig. 14 $\overline{v't'}$ profile measured by Shome & Wang (1991) for a transitional boundary layer with $Re_x = 8.82 * 10^5$, with nominal intermittency of 0.9.

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13. ABSTRACT (*Maximum 200 words*)

During an experimental investigation of the transitional boundary layer over a heated flat plate (Sohn and Reshotko 1991), an unexpected result was encountered for the turbulent heat flux ($\overline{v't'}$). This quantity, representing the correlation between the fluctuating normal velocity and the temperature, was measured to be negative near the wall under certain conditions. The result was unexpected as it implied a counter-gradient heat transfer by the turbulent fluctuations. Possible reasons for this anomalous result were further investigated. The possible causes considered for the negative $\overline{v't'}$ were: (1) plausible measurement error and peculiarity of the flow facility, (2) large probe size effect, (3) "streaky structure" in the near-wall boundary layer, and (4) contribution from other terms usually assumed negligible in the energy equation including the Reynolds heat flux in the streamwise direction ($\overline{u't'}$). Even though the energy balance has remained inconclusive, none of the items (1), (2), and (3) appear to be contributing directly to the anomaly. Recently, a similar negative turbulent heat flux was also measured by another researcher, however, physical mechanisms leading to the result remain unexplained.

14. SUBJECT TERMS

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